Mykhaylo ZAGIRNYAK[1], Viacheslav PRUS[1], Atef Saleh ALMASHAKBEH[2]
[1]Kremenchuk Mykhailo Ostrohradskyi National University, Ukraine
[2]Tafila Technical University, Jordan

doi:10.15199/48.2020.02.25

The substantiation and research of the alteration of the characteristics of electric machines in the course of long-term operation

Abstract. *A system approach to the determination of the operation parameters of electric machines with long time between failures is substantiated It allows taking into account the specific features of the change of the state of their basic structural units. The high efficiency and reliability of the proposed approach from the point of view of the assessment of the nameplate data, energy components, vibration and thermal parameters of such electric machines are experimentally confirmed.*

Streszczenie. *W artykule wskazano na zasadność systemowego podejścia do wyznaczania parametrów pracy maszyn elektrycznych z długim czasem między awariami. Pozwala to uwzględnić specyficzne cechy zmiany stanu ich podstawowych jednostek konstrukcyjnych. Wysoka wydajność i niezawodność proponowanego podejścia z punktu widzenia oceny danych z tabliczki znamionowej, składników energii, wibracji i parametrów termicznych takich maszyn elektrycznych jest eksperymentalnie potwierdzona. (**Badanie zmian właściwości maszyn elektrycznych w trakcie długotrwałej pracy**)*

Keywords: electric machine, structural unit, defect, thermal process, thermal image control.
Słowa kluczowe: maszyna elektryczna, jednostka konstrukcyjna, wada, proces termiczny, analiza termogramu

Introduction

In the process of long-term operation and repair of electric machines (EM) their basic parameters and characteristics change [1]. It is mainly explained by aging of EMs and their structural units both naturally and under the influence of the violation of the service and storage conditions, etc. and by the impossibility of the provision of the required quality of the repair work [2]. In practice, EM aging process is not subject to generalized assessment because of the absence of interrelations between EM unit state and the main groups of their operation parameters [3]. That is why, in most cases, engineers limit themselves to a small set of parameters characterizing certain deviations in EM operation, such as changes of vibration, temperature, energy consumption parameters, etc.

The absence of systematization in the considered problem is chiefly explained by technical and economic reasons as, while operating EM, one just seeks to achieve the minimum of the modified current expenditure. In this case, the main problem for important groups of mechanisms and non-power-consuming productions consists in the provision of their required reliability. At the same time, for power-consuming technologies and productions it is necessary to balance comprehensively the expenditure for the restoration and maintenance of EM operability (maintenance and repair costs) and the expenditure for their current operation (electric energy costs). Thus, depending on the purpose and specific features of the mechanism, wherein EMs are installed, the aim of operation consists in the increase of their time between failures and (or) power efficiency. It is from these points of view that EM aging processes are to be assessed.

Therefore, the purpose of the paper consisted in the systematization of the previously performed research for the substantiation of the interrelations of the basic operation parameters of EMs with long time between failures with the specific features and the degree of aging of their main structural units.

Theory

Most often, we systemize EM damages and defects by the statistics of their failures. In this case, we do not specify the causes of the failures. Besides, we neglect the change of the properties of the structural units and elements. It allows us to say that most EM failures are caused by the break of winding insulation, failure of bearings, etc.

However, if we look at this problem more widely, we can see that the initial cause of most failures lies in the change of the properties and local damages of particular structural units. They may include cooling fins shears, local damages of shafts, bearing sites and many others.

Electrical steel is one of important structural elements whose properties influence most EM parameters and characteristics. In the process of long-term operation, alternating with repairs, it has both a deterioration of the magnetic structure itself and the destruction of the inter-sheet insulation of cores [4]. These changes are shown in Table 1 and additionally demonstrated in Figs. 1–2 by the example of 2013 electric steel.

Curves 1 and 3 in Figs. 1–2 correspond to the initial state and the state after the first anneal for the core made of insulated sheets, curves 2 and 4 correspond to the initial state and the state after the first anneal for the core made of sheets without insulation. They indicate moderate growth of total specific losses p in the course of steel natural aging with the increase of the relative part of the eddy current losses (the growth of frequency degree coefficient α). At the same time, as Figs. 1–2 demonstrate, the manifestation of this phenomenon at the value of magnetic induction that does not exceed 1 T is insignificant.

The general aging of laminated steel shows in the reduction of the level of saturation magnetic inductance B_s at the decrease of the inclination angle β_1 of the saturated section of the magnetizing curve (Fig. 1), and a sharper growth of specific losses characterized by the increase of angle β_2 (Fig. 2). In this case, the presence of inductance B'_m, is characteristic of Figs 1–2. It corresponds to the breakpoints of both the magnetizing curve and the dependence for specific losses. Though the deterioration of these parameters takes place against the background of reduction of magnetic field strength H , having analyzed the ranges of the real change of magnetic inductance, one can conclude that the real deterioration of the laminated cores properties is much stronger.

Table 1. The results of the research of the change of the properties of 2013 electric steel

Parameter	Initial value	Change limit, %	Repair (anneal), %	Operation, %
$p_{1,0/50}$, W/kg	2.62	+43.4	+5.41 +10.8 +18.6	+4.34
α	1.54	+29.8	+7.24 +16.5 +25.9	+6.12
B_s, T	1.56	–25.7	–12.3 –18.7 –21.2	–7.21
H, A/m	1123	–10.9	–3.32 –4.87 –6.25	–2.72

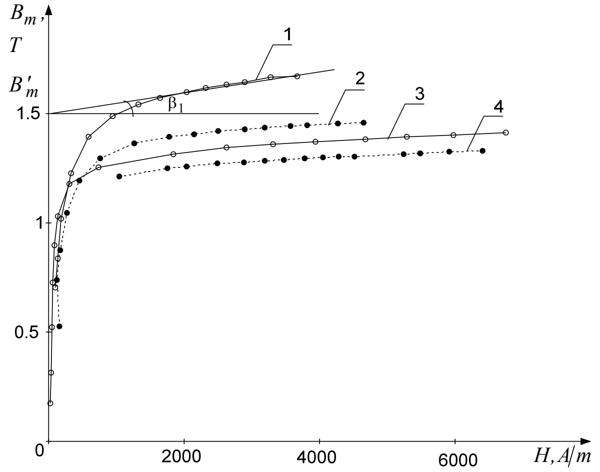

Fig. 1. Dependences $B_m = f(H)$ of magnetic inductance on magnetic field strength

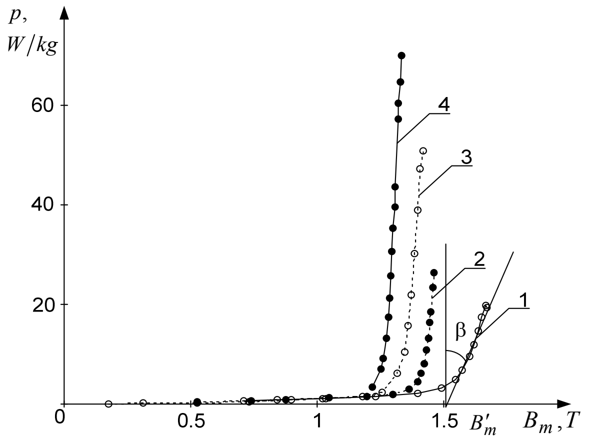

Fig. 2. Specific loss dependences $p = f(B_m)$ on magnetic inductance

In addition, such violations are most often local, which causes the magnetic and electrical asymmetries of EM structures.

The considered reasons are manifested in the phase-by-phase discrepancy of the electromagnetic parameters of the typical equivalent circuits [5]. This significantly complicates both the calculation of the magnetizing circuit and the windings, for which typical calculation methods are not applicable in conditions of high saturation of the magnetic system [2].

The real scatter of the values of electromagnetic parameters, as shown in [5], can be on average from 3–7% for winding resistive impedance to 35–90% for the parameters of the magnetizing circuit. These changes should be taken into account by making corrections to the operation of control systems for such EMs [6].

The following group, important for EM operation, includes the power parameters that determine the power efficiency of the system as a whole. They include power coefficients and loss components. Their determination is also characterized by the complication of the used methods and the calculated relations due to the oversaturation of the magnetic system [7]. Moreover, to analyze the dynamic processes a mandatory transition to instantaneous power values is necessary [2, 7].

The limits of change in the power parameters of the EM – separate-excitation (SE) direct current machines (DCM) or machines with permanent-magnet excitation, induction motors (IM) with squirrel cage rotor (SCR) or phase wound rotor (PWR) – of the researched power range are shown in Table 2. Here P_{cu} – copper losses; P_{ex} – excitation losses; P_b – brush losses; P_{mec} – mechanical losses; P_μ – magnetic losses (steel losses); P_{add} – additional losses; η – efficiency; $\cos\varphi$ – power coefficient

Table 2. The results of the experimental determination of the power parameters of a low-power EM

Parameter	DCMt SE	IM with SCR	IM with PWR
P_{cu}	+0.39–2.17	–	–
P_{cu1}	–	+1.71–4.82	+2.46–6.13
P_{cu2}	–	+0.73–2.91	+2.25–4.97
P_{ex}	+0.42–1.91	–	–
P_b	+0.71–1.53	–	+2.14–3.27
P_{mec}	+4.18–13.6	+2.12–2.78	+10.28–22.34
P_μ	+8.22–27.8	–	–
$P_{\mu 1}$	–	+7.96–43.9	+10.32–54.4
P_{add}	–	+10.7–53.5	+12.6–61.0
η	–0.56–3.24	–0.91–2.68	–1.37–3.15
$\cos\varphi$	–	+17.6–23.3	+12.3–19.6

As can be seen, the change in the properties of the structural units and elements of the EM during aging fundamentally alters the distribution of losses, which cannot but affect the deterioration of the power efficiency of the EM.

Special attention should be paid to local deterioration of the properties, e.g. of laminated steel. As an example, IM in [8] shows that it may cause a redistribution of vibration-exciting forces. As a result, the electromagnetic components of vibration increase dramatically.

A local change in the properties of steel also affects the temperature redistribution of the EM windings. Firstly, the calculation itself becomes more complicated either by moving from simple thermal equivalent circuits to more complex calculation equations or to sectional equivalent circuits [9]. In some cases, to ensure the required accuracy of calculations, it is necessary to take into account the local change in the coefficient of thermal conductivity. Secondly, the location of the temperature maximum varies in an arbitrary way, for the example, along the length of IM stator winding (Fig. 3). Here a dotted line marks the transition between the front and slot parts of the winding. Dependence 1 is calculated taking into account the steel properties changes (including the local ones), dependence 2 – without taking them into account.

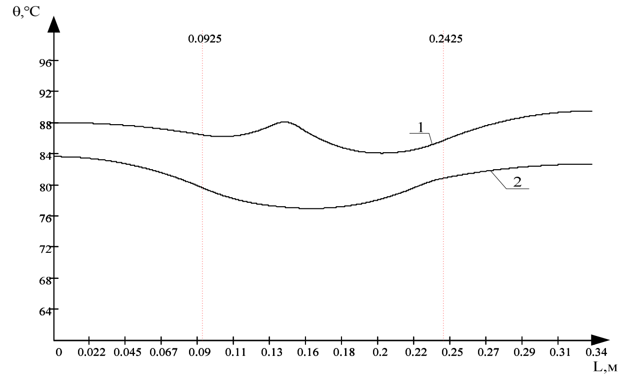

Fig. 3. The profile of the change of the temperature excess θ along the length of the stator winding

These changes substantiate the transition to more complex, intelligent methods for calculating reliability. The terms of their use are explained in [10]. In this case, the experiment planning theory can be applied only to particular structural units and elements, as shown in [11]. However, even in the case of seemingly simple units, such as bearing units, the use of fuzzy logic [12] and various types of neural networks [13] provides much better results. As a result, the most accurate reliability models combine these approaches [14].

The results of the systematization of the interrelation of EM basic parameters and characteristics with the state of structural units and the substantiation of its information value/necessity and the methods for the determination of the parameters for each group are given in Table 3.

Experimental research

Complex research of EM with long time between failures – induction motor 4A90L6U4 was performed to test the statements of Table 3, and their results are shown in Table 4. The obtained results confirm the efficiency and reliability of the proposed approach.

Table 3. Interrelation between EM parameters (characteristics) and the state of the structural units

Reg. No.	Name of parameter/characteristic group	Relation to structural unit state	Information value (necessity for determination)	Determination methods
1.	Magnetic and electrical parameters and characteristics of magnetic circuits	Determine the deterioration of the properties of EM magnetic circuit (mainly laminated)	Allow forecasting the alteration of the properties of EM magnetic system	Induction local testing method
2.	EM winding parameters	Determine the state of EM windings, mainly the presence, type and degree of their damage	Provide the possibility for specified determination of the degree of the winding damage in the presence of turn-to-turn short circuits	Specified pulse-resonance method, the assessment of the intensity and the character of transient processes
3.	EM electromagnetic parameters (the parameters of the corresponding equivalent circuits are their basis)	Allow complex assessment of EM current state influence on their operation parameters	Enable the correction of the parameters of EM power efficiency and reliability both in the presence and absence of a control transducer	Refined equivalent circuits and modified methods taking into account the change of the degree of EM magnetic system saturation
4.	EM power parameters and characteristics, including instantaneous ones	Provide the possibility to assess the losses components redistribution by EM main units as well as the efficiency in steady and transient operation modes	Allow transition to direct control of EM by the power criteria, which makes it possible to essentially improve the power efficiency	Refined methods for the determination of losses components and EM efficiency
5.	EM rated published data and performance characteristics	Specify the complex alteration of EM basic parameters and characteristics in the rated mode and with operation load on the shaft	Allow the assessment of the possibility and expedience of the operation of every separate EM under particular technological conditions	Specified confirmatory calculation methods
6.	EM thermal parameters	Enable forecasting the real excess of EM windings temperature	Provide the possibility of assessment of EM overloading capacity in the system of technical and economic indices	Specified thermal schemes and calculation methods taking into account the irregular distribution of heating losses and thermal conductivity
7.	EM vibration parameters	Allow identification of EM damaged units and the degree of their damage	Enable forecasting EM maintenance and repairs by the current state	Vibration diagnostic methods, field methods of forecasting the alteration of vibration parameters
8.	EM reliability indices	Provide the possibility of transition to the assessment of EM state based on the state of its main structural units	Enable forecasting EM reliability indices taking into account the current state of the basic structural units	Experiment organization and planning methods, intelligent methods for the assessment of EM reliability

Table 4. The results of the calculation of the parameters of 4A90L6U4 IM

Parameter	Designation	Experiment, %	Calculation range, %
Nameplate data			
Power on IM shaft	P_{2n}	–2.20	–1.2–5
Stator current	I_{1n}	+1.56	+1.5–4.8
Power coefficient	$\cos\varphi_n$	–0.78	–1.1–3.3
Efficiency	η_n	–2.23	–1.5–4.5
No-load operation parameters			
Idle running current	I_0	+14.97	+7.5–28
Idle running losses	P_0	+35.5	+12–41
Changing loss components			
Stator steel losses	$\Delta P_{\mu 1}$	+41.47	+10.1–

			42.5
Stator copper losses	ΔP_{cu1}	+3.69	+2.52–5.79
Vibration and thermal parameters			
Average growth of temperature	$\Delta\theta_{av}$	+2.7	+5.12–27.8
Maximal temperature excess	$\Delta\theta_{\max}$	+13.4	+7.63–21.2
The highest drop of vibroexcitating force	ΔF_{ve}	–	+29.7
Vibration velocity excess along the main axis	Δv	+14.9	+7.63–18.5
Admissible parameters of the load mode			
Stator current	I_{1ad}	–3.12	–3.03–10.24
Power on IM shaft	P_{2ad}	–10.93	–10.5–24.3
Mean time between failures (forecast)	T_{rh}	–30.4	–25.7–33.2

Conclusions

1. Systematization has been performed, and the approach to the determination of EM operation parameters, taking into account the specific features and the degree of aging of their basic structural units, has been substantiated.
2. The higher efficiency and reliability of the proposed method from the point of view of the assessment of the basic operation parameters of EM with long time between failures has been experimentally confirmed.

***Authors**: Mykhaylo Zagirnyak, Rector of Kremenchuk Mykhailo Ostrohradskyi National University, Professor, vul. Pershotravneva, 20, 39600, Ukraine, e-mail: mzagirn@kdu.edu.ua; Viacheslav Prus, Associate Professor of the Department of Electric Machines and Devices of Kremenchuk Mykhailo Ostrohradskyi National University, vul. Pershotravneva, 20, 39600, Ukraine, e-mail: prus@kdu.edu.ua; Atef Saleh Almashakbeh, Associate Professor of Faculty of Engineering, Tafila Technical University, Postal code 66110, P.O. Box 179-Jordan, e-mail: dr.almashakbeh@gmail.com.*

REFERENCES

[1] Hamid A. Toliyat, Subhasis Nandi, Seungdeog Choi "Homayoun Meshgin-Kelk", *Electric Machines: Modeling, Condition Monitoring and Fault Diagnosis*, CRC Press, October 30, 2012.
[2] M. Zagirnyak, V. Prus, D. Miljavec "Improved method for calculation of parameters of electromagnetic and power processes in electric circuits with steel in saturation mode", *Technical Electrodynamics*, № 4, 2015, pp. 12–18.
[3] M.V. Zagirnyak, V.V. Prus, A.V. Nikitina "Grounds for efficiency and prospect of the use of instantaneous power components in electric systems diagnostics", *Przeglad Elektrotechniczny* (*Electrical Revue*), № 12, 2006, pp. 123–125.
[4] V. Prus, A. Nikitina, M. Zagirnyak, D. Miljavec "Research of rnergy processes in circuits containing iron in saturation condition", *Przeglad Elektrotechniczny* (*Electrical Revue*), № 3, 2011, pp. 149–152.
[5] M. Zagirnyak, V. Prus "The special features of the change of electromagnetic parameters of electric machines with long mean-time between failures", *Przeglad Elektrotechniczny* (*Electrical Review*), No 1 (94), 2018, pp. 117–120.
[6] M. Zagirnyak, A. Kalinov, A. Chumachova "Correction of operating condition of a variable-frequency electric drive with a non-linear and asymmetric induction motor", *IEEE EuroCon 2013*, 2013, pp. 1033−1037.
[7] V. Prus "The alteration of the energy parameters and losses components of electric machines in the process of their aging", *Proceedings of the International Conference on Modern Electrical and Energy Systems*, *MEES 2017*, 2018, January, pp. 44–47.
[8] M. Zagirnyak, V. Prus, I. Kolotylo, D. Miljavec "Taking stator cores into account when induction motors vibration parameters are calculated". *Przeglad Elektrotechniczny* (*Electrical Review*), No 12, 2013, pp. 192–195.
[9] M. M. Fedorov "The improvement of the methods for forecasting the thermal state of alternating current electric motors in the unsteady conditions of their operation", *Doctor's thesis in specialty 05.09.01. Electric machines and devices*, Kharkiv, NTU KhPI, (2003). 36 p. (in Ukranian).
[10] N. F. Kotelenets, N. L. Kuznetsov "Testing and reliability of electric machines", Moscow, *Vysshaia shkola*, 1988, (in Russian).
[11] A. S. Almashakbeh, M. Zagirnyak, V. Prus "Models or electric machine reliability prediction at variation of the condition of basic structural units", *Przeglad Elektrotechniczny* (*Electrical Review*), R. 93 №1, 2017, pp. 117–120.
[12] M. Zagirnyak, V. Prus, O. Somka, I. Dolezel "Models of Reliability Prediction of Electric Machine Taking into Account the State of Major Structural Units", *Advances in Electrical and Electronic Engineering*, Vol. 13 № 5, 2015, pp. 447–452.
[13] M. Zagirnyak, V. Prus "Use of neuronets in problems of forecasting the reliability of electric machines with a high degree of mean time between failures", *Przeglad Elektrotechniczny (Electrical Review)*, R. 92 № 1, 2016, pp. 132–135.
[14] M. Zagirnyak, V. Prus, O. Somka "Reliability Models of Electric Machines with Structural Defects", *Proceedings 2015 16th International Conference on Computational Problems of Electrical Engineering* (*CPEE*), Lviv, Ukraine, 2015, pp. 249–251.